Low Level RF System Design for the PEP-II B Factory*

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Abstract

Heavy beam loading in PEP-II has driven the design of the low level RF system to contain feedback loops similar to those used in proton rings. The RF feedback loops control longitudinal coupled-bunch instabilities caused by the beam interaction with the accelerating mode of the RF cavities by reducing the cavity impedance observed by the beam. The RF system employs a modular design housed in a VXI environment and uses the EPICS control system. Modern control system design and signal processing is used throughout the system. This paper describes the RF system topology and the signal processing used to fulfill the system requirements.

1. INTRODUCTION

As discussed in previous papers [1][2], a fundamental requirement for the PEP-II RF control system is the need to control longitudinal coupled-bunch instabilities caused by the interaction of the beam with the accelerating mode of the RF cavities. This task will be handled by a combination of three feedback loops (Figure 1). The direct loop reduces the growth rate of the most strongly driven modes. The effectiveness of this loop is proportional to the total system group delay and is the reason for specifying a short klystron group delay (<150ns) over the necessary bandwidth (~1 MHz).

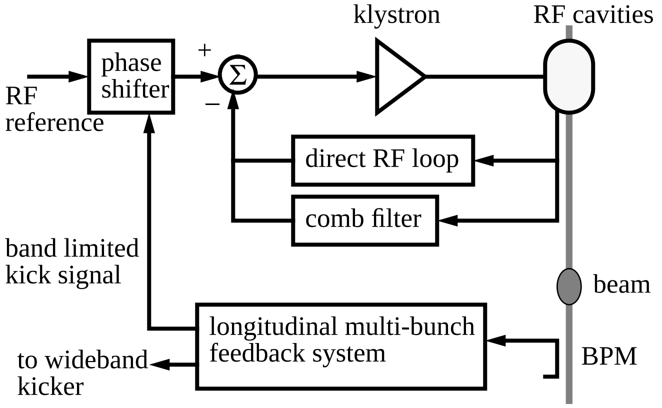

Fig. 1. Block diagram of RF feedback loops planned to control longitudinal instabilities driven by the fundamental mode.

The comb filter loop provides additional gain but only over a narrow band about each synchrotron sideband. The comb loop response operates around the direct loop damped cavity resonance providing gain to synchrotron sidebands over a span of several MHz. Together these two loops bring growth rates down from a few microseconds to several milliseconds.

The longitudinal multi-bunch feedback system will provide the final damping necessary to control the instability [3]. Only a few MHz of the available 500 MHz bandwidth can be passed through the klystron, so a filtered "kick" signal will be transmitted by each RF station. This signal operates through the closed-loop response of the klystron/cavity combination and is therefore very insensitive to system variations. In short the RF system becomes a powerful "sub-woofer" for the multi-bunch feedback system. Simulations show that these three feedback loops will provide a final damping rate of <500 turns in the most demanding 3 Amp. low energy ring (LER) case [4].

2. SYSTEM RF SIGNAL FLOW

The comb filters are implemented digitally as second order IIR filters followed by a 32 tap FIR group delay equalizer and a programmable 1-turn delay with 25 ns resolution. The 476 MHz RF carrier must be quadrature down-converted to baseband before being sampled. We have decided to implement all the RF signal processing at baseband. Figure 3 is a RF signal flow diagram for a PEP-II high energy ring (HER) station. A low energy ring (LER) station contains two cavities.

RF from each cavity is down converted to baseband using an I/Q detector. Each detector produces analog signals proportional to the real (I) and imaginary (Q) components of the RF signal with respect to the reference 476 MHz provided to each detector. To produce a signal proportional to the total station gap voltage, each of the baseband cavity signals must be phase shifted and scaled. This requires a 2-by-2 analog matrix multiplier with programmable coefficients and low group delay (Figure 2). Automated calibration routines will adjust the combining network and remove offsets.

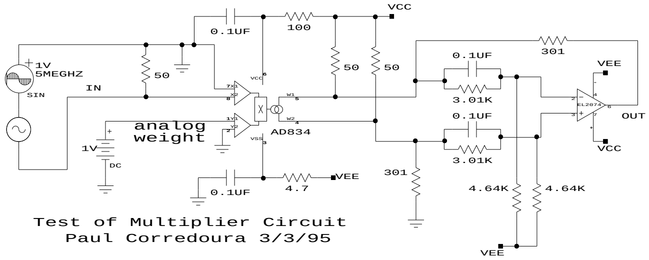

Fig. 2. Schematic of wideband dc-coupled multiplier used in the baseband I/Q modulator. Measured group delay is only 5 ns.

The baseband station gap voltage I/Q signals enter another I/Q modulator to allow adjusting the direct RF feedback loop. A parallel path exists to feed the digital comb filters. Another I/Q modulator follows the comb filters for loop parameter adjustment. Outputs of the two loops are combined and then subtracted from the baseband station RF reference. The reference signal also contains a phase modulation "kick" from the longitudinal multi-bunch feedback system. The I/Q error signals then pass through a PID controller. Lead compensation enhances the performance of the direct RF loop while integration reduces DC errors which directly translate to the 476 MHz system RF carrier.

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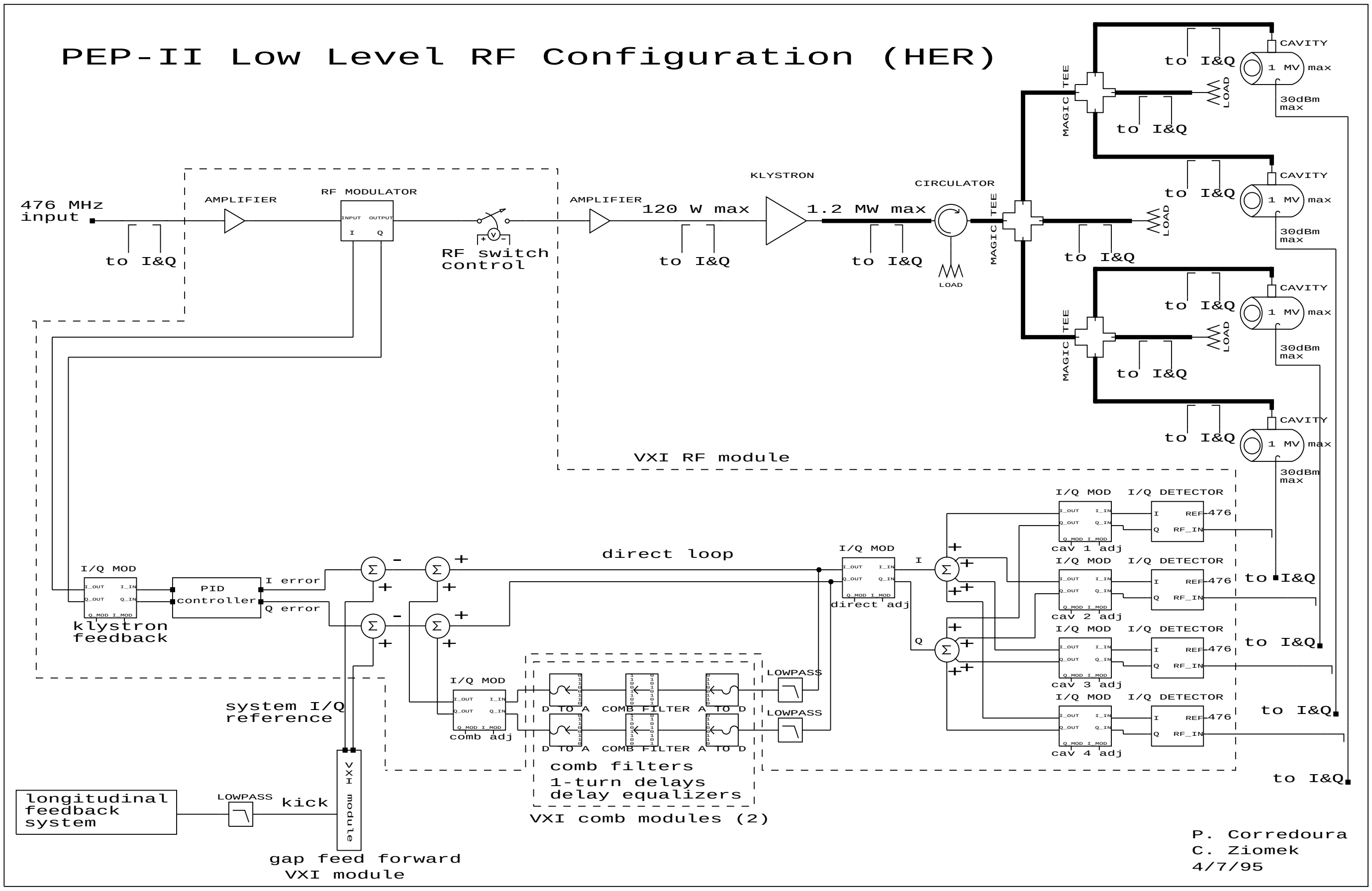

Fig. 3. Block diagram of a HER RF station showing down-conversion to baseband, signal processing and up-conversion to RF.

The signals pass through a final baseband I/Q modulator which is used to implement a digital feedback loop around the up-converter, pre-amplifier and klystron. This loop will be described in detail later in this paper. The final baseband drive signals are next up-converted to 476 MHz using a RF I/Q modulator. High level mixers are used in this device to minimize errors and to allow driving the solid-state klystron pre-amplifier directly. This topology removes the need for a RF limiter to protect the input stage of the solid-state amplifier.

3. ADDITIONAL CONTROL LOOPS

A multi-channel I/Q detector is being developed to create a modular RF measurement and control system [5]. Each channel will be capable of digitally measuring the I/Q components of the RF carrier over a programmable bandwidth producing non-aliased measurements for output rates ranging from 25 Hz to above 50 kHz. Errors will be <0.05° in phase and <0.1% in amplitude at a 5 kHz data rate. Proposed measurement locations are labeled as “to I&Q” in figure 3. Using this approach it becomes natural to implement digital control for cavity tuners, gap voltage, station phase, and klystron ripple reduction.

Klystron high voltage power supply (HVPS) ripple causes mainly phase modulation, although some amplitude modulation may also be present. The modulation appears at multiples of 60 Hz with the largest component at 720 Hz due to the power supply transformer configuration. This situation lends itself well to a digital control technique known as disturbance estimation. Since the modulation (disturbance) is composed of several superimposed sinusoids at known frequencies, a state-space error estimator can be designed to track and cancel them [6]. Using digital I/Q information, the output phase and amplitude is calculated, compared to desired values and delivered to two separate state-space disturbance estimators. The estimators converge on the errors which are then subtracted from the system baseband reference. Analysis shows that disturbance reductions of 40 dB are possible.

A simulation of the klystron feedback loop was made using the Simulink control system analysis software package. The superposition of a 720 Hz sinusoid and a step function forms the disturbance for both phase and amplitude. The phase disturbance estimator was augmented with an integration function to track dc errors, this feature is not useful in the amplitude loop. White noise was also injected into each I/Q measurement. The sample rate was 5 kHz. Results of the simulation are shown in figure 4. Note that the 720 Hz phase error is effectively cancelled in 50 ms and the step disturbance is also removed. The amplitude error plot shows cancellation of the 720 Hz while ignoring the step. In each case the convergence rate of the estimators is completely programmable. Slower convergence yields greater noise immunity. In the actual PEP-II implementation the estimators will be designed to track all the necessary power line harmonics.

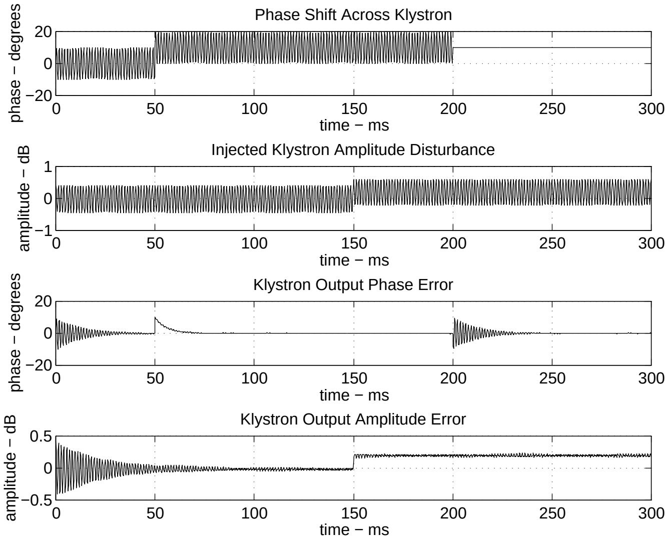

Fig. 4. Simulation of klystron ripple cancellation.

There are several other feedback loops, all of which will be implemented digitally. The baseband station I/Q reference must track the cavity transients caused by the ion clearing gap to prevent the klystron from reaching saturation. An adaptive feed-forward algorithm for minimizing klystron output power variation on a 1-turn basis has been developed and simulated [4]. The algorithm produces a station RF reference which minimizes the variation of the average klystron drive power. The adaption rate is designed to be slow compared to all the feedback loops in the system. In simulation this procedure reduces the klystron output power variations down to a few kW with a 5% beam gap.

The PEP-II klystrons will not contain collectors capable of absorbing the full 2 MW maximum available klystron beam power. A feedback loop measuring the klystron high voltage power supply output and the delivered RF power will be used to program the operating voltage. The goal will be to keep the klystron operating a fixed amount below saturation to insure sufficient AM gain for the RF feedback loops. Electrical efficiency also benefits from this strategy. Since the phase shift across the klystron varies by ~14°/kV, the klystron phase loop discussed earlier must be capable of providing a large range of continuous phase shift. With the I/Q topology, phase may be rotated infinitely without discontinuities by simply applying the proper analog weights to the baseband I/Q modulator.

The PEP-II RF control system will also contain the “standard” feedback loops to control gap voltage, station phase and cavity tuners for each station. In addition to minimizing reflected power, the tuner loop must also balance the power delivered to each cavity. Each of these will also be implemented digitally. A major advantage of this approach is that configuring loops or adding new ones becomes a software task - provided that the measurement and control ports are already hardware supported. A programmable I/Q source will be included in the RF module to allow measuring loop responses by injecting white noise or a swept sinusoid. This feature will allow the possibility of automated calibration and remote operation.

4. SYSTEM HARDWARE TOPOLOGY

A PEP-II low-level RF station will be composed mainly of modules in a VXI crate. Like CAMAC, VXI has an addressable data bus and standard power supply voltages. VXI goes further to provide more power supply voltages, larger module size, better shielding and standards for neighboring modules to pass analog and digital information. With the planned baseband signal processing, many system connections can take advantage of the local bus connections effectively eliminating many external connections. Fast interlock functions for window arc detection and excessive klystron reflected power use VXI shared trigger lines to remove RF drive and fire the HVPS crowbar. The VXI module layout planned for PEP-II is shown below in figure 5.

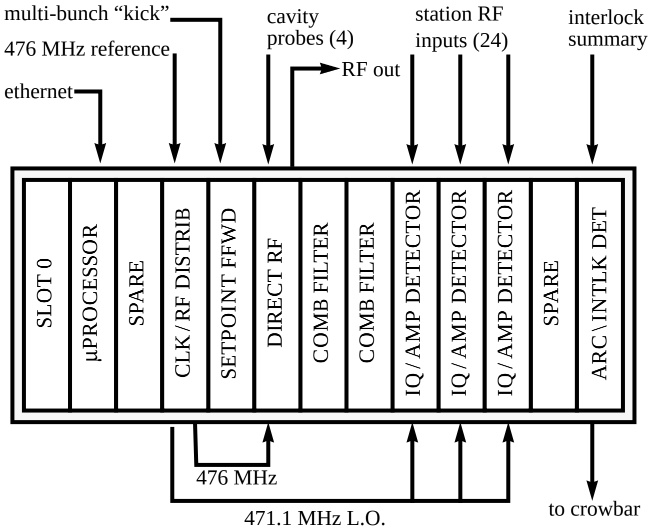

Fig. 5. Planned PEP-II HER VXI Crate Layout.

5. SUMMARY

The PEP-II low-level RF system design described is modern, cost effective and extremely flexible. The system is easily transportable and could be considered for use in other storage rings. Future papers will describe test results as the system is constructed.

6. REFERENCES

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